Application of Statistical Methods in Rainfall Analysis and Extreme Weather Events

SHORT SYNOPSIS

Submitted in partial fulfillment of the requirement of the degree of

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by

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Registration number: 21/Ph.D/112

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Certificate

I hereby declare that the short synopsis **"Application of statistical methods in rainfall analysis and extreme weather events"** being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in mathematics under School of engineering and technology of Manav Rachna International Institute of Research & Studies, Faridabad during the academic year 2021-22 winter batch.

It is a bona fide record of original work carried out under the supervision of **Dr. Deepak Kumar** and Co- supervision of **Dr. Shashikant** has not been submitted in full or part to any other university or institute for degree or diploma. Further, it is certified that short synopsis is plagiarism free and proof has been submitted.

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ABSTRACT

Rainfall (RF) analysis can have many benefits, including Climate predictions, urban planning, water resource management, transportation safety, disaster risk reduction, agriculture production, etc. Due to population growth, urbanization, and development, the demand for water is increasing in this area day by day. Statistical techniques are vital for examining RF trends and severe weather events. Statistical techniques assist in comprehending historical patterns, forecasting future occurrences, and evaluating risks linked to climate fluctuations. Thus, analyzing the probability of RF is essential to tackle various water management problems and to prevent crops from damage caused by excessive RF. A trend analysis is conducted using the non-parametric Mann-Kendall(M-K) test. A thorough trend analysis is conducted based on monthly, seasonal, and yearly data.

The RF data is examined using different probability distribution (PD) including Gumbel (1941), Chow (1964), Log Pearson type-III, and Log Normal to forecast annual maximum RF over one day, two consecutive days, and three consecutive days, while assessing the goodness of fit through Chi-Square, percentage absolute deviation (PAD), and integral square error (ISE). This work utilized the RF data to grasp climate patterns and shifts, applying that knowledge across various fields.

Keywords: Rainfall, Trend analysis, Precipitation, PD, Mann- Kendall(M-K) test, Monsoon.

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INTRODUCTION:

Globally, the water demand is increasing due to urbanization, economic development, and population growth. RF is a crucial part of the balance of the natural hydrological cycle. The study of the characteristics of RF becomes important, especially in urban areas, in light of changing climate patterns. The Indian summer monsoon RF (ISMR) is a major source for the availability of fresh water for drinking, sanitation, water resource management, the economy, developmental projects, and agricultural activities. Therefore, the analysis of the Indian Summer Monsoon RF (ISMR) is very important for decision-making and planning purposes.

The analysis of successive days of peak monsoon seasonal RF and yearly maximum RF across various return periods serves as a fundamental resource for ensuring safety and designing small dams, bridges, irrigation, drainage projects, economic planning, and the agricultural sector, among others. The characteristics of RF depend on time and space.
An examination of the yearly and seasonal RF for different return periods has been presented (Singh and Upadhaya, 1998) using PD such as Normal distribution, Log Pearson type-III, Gumbel distribution, Gamma distribution, and Beta distribution. At present, numerous studies have been carried out in India, mainly concentrating on verifying the statistical techniques of different PD like Gamma, Gumbel, and Log Pearson type-III for planning in watershed management, agriculture, safe drinking water, and economic growth.

A detailed trend analysis has been done in various cities using both the parametric (t- test) and non – parametric test (Mann, 1945; Kendall, 1975) provides increasing and decreasing trends and also provides a positive and negative correlation between the seasonal and annual RF for a given level of significance. The amount of RF an area experiences is a crucial aspect in assessing the quantity of water accessible for different needs, including agriculture, water supply, and hydroelectric power production.

The aim of this current study is to examine the patterns of monthly, seasonal, and annual RF, predict future trends, and assess the environmental impact through the application of non-parametric tests like the M-K test, Sen's Slope estimator, Coefficient of Variation, Auto Correlation, Linear Regression, SM Oreg, and CA-ANN analysis.

Some steps for analyzing RF data include:

- **Data collection**: Obtain reliable RF data from sources like weather stations or meteorological agencies.
- **Data cleaning**: Check for missing or inconsistent data points.
- **Data exploration**: Visualize the data through plots and graphs.
- **Temporal analysis**: Examine temporal trends by plotting RF over time.

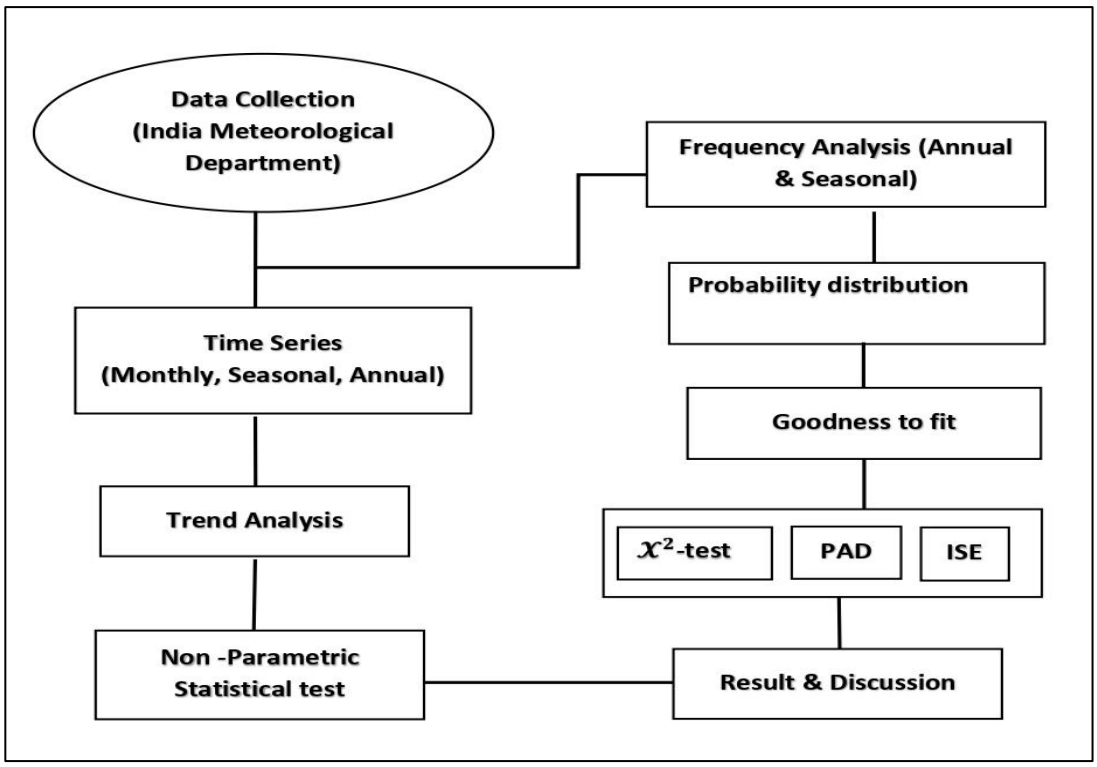

Fig.1 Flow chart methodology for analyze the RF data

DESCRIPTION OF BOARD AREA:

Rain consists of liquid water droplets that have formed from the condensation of atmospheric water vapor. In the water cycle, precipitation plays a crucial role. Rain assists in watering crops and also manages the freshwater that settles on the earth.

RF can be classified into three categories, which are listed below:

- Convectional RF

- Relief or Orographic RF
- Frontal or Cyclonic RF

Essential Requirements for RF

Moisture Source: RF depends on moisture from oceans, seas, rivers, and lakes. Elevated humidity guarantees sufficient water vapor is present for condensation.

Air Cooling: For condensation to take place, air needs to lower in temperature, which can occur via ascent or by touching cooler surfaces.

Condensation Nuclei: Small particles such as dust or salt serve as condensation nuclei, aiding water vapor in forming droplets.

Air Saturation: For condensation to start, air must attain 100% relative humidity, which results in cloud creation and precipitation

Types of RF based on Intensity:

As per the India Meteorological Department, the classification of the intensity of RF is given in Table 1

Table 1: Classification of the intensity of RF (Source: IMD)

Category	24 hours cumulative RF (mm)
No RF	0.0
Drizzle RF	0.1-2.4
Light RF	2.5-15.5
Moderate RF	15.6-64.4
Intense RF	64.5-115.5
Extremely Heavy RF	115.6-204.4
Intensely Heavy RF	>204.4

It is important to note that RF denotes cumulative RF during 24 hours 03 Universal Coordinated Time UTC to the previous day to 03 UTC of present day. The same definition is used in this study to identify the rainy days.

Examining RF in India is essential for grasping monsoon trends, managing water resources, and assessing the effects of climate change. Here's a comprehensive summary:

Monsoon-Predominant: Approximately 75-80% of India's yearly precipitation takes place during the Southwest Monsoon (June-September).

Four Periods of RF:

Winter (January-February): Minimal RF, primarily in Northern India.

Pre-monsoon (Mar-May): Thunderstorms cause rain in various regions of the country.

Monsoon (Jun-Sep): Intense precipitation from the southwestern monsoon.

Post-monsoon (Oct-Dec): The northeast monsoon delivers RF to Tamil Nadu and southern Andhra Pradesh.

LITERATURE REVIEW:

Many studies in the literature have examined RF patterns across various geographical locations. One such research on RF trends and variability in Kolkata has been conducted by Sikh et al. (2023), Their analysis utilized RF data spanning 119 years (1901–2019) and applied non-parametric statistical methods M-K test and Sen's Slope estimators for monthly, seasonally and annually. Their assessment indicated a positive trend in pre-monsoon, monsoon, post-monsoon, and yearly RF, whereas winter RF exhibited a negative trend. In the post-monsoon season, the most notable rise in RF was recorded at 0.365 mm annually, while the least rise, 0.2325 mm annually, took place in the pre-monsoon season. Conversely, winter precipitation decreased significantly by -0.0135 mm annually. Winter precipitation showed the greatest coefficient of variation (72.89%), while yearly precipitation recorded the lowest coefficient of variation (17.68%).

The RF trend analysis in Delhi and Mumbai for 54 years (1951- 2004) has been done by Rana et al. (2012). The RF data were analyzed monthly, seasonally, and annually and also

determined the trend by non-parametric statistical method M-K test and linear regression. In this study, it was found that the capital city Delhi experienced an insignificant long-term decreasing trend in the southwest monsoon, while Mumbai showed a slightly significant long-term decreasing trend.

The RF analysis and temperature trend in Beni City, Democratic Republic of Congo, from the period of 31 years (1990-2020) has been done by their study revealed significant warming and increased RF, both annually and seasonally, in the region. Earlier studies have also addressed related topics: Bhakar et al. (2006) performed the probability analysis of consecutive days with different return periods. Common probability distribution functions used for estimating precipitation frequency include Gumbel, Ven Te Chow, Log Pearson Type III, and Log Normal, as discussed by Chakraborty et al., (2012).

In another study, the RF probability analysis for the period of 1980-2013 (34 years) for the district of Allahabad was investigated by Asim & Nath (2015), their study showed that the Gumbel distribution (GD) and Log Normal method were determined to be the top two models for forecasting annual maximum RF, in that order.

The frequency analysis of the annual maximum RF of 30 years from the period 1991-2000 for the Roorkee district of Uttarakhand has been done by Kaur et al. (2021). Their analysis revealed that the GD was found the first-best fit and Ven Te Chow was the second-best fit model for the prediction of annual maximum RF. During last two decades, the analysis of southwest monsoon has been done by Kant et al. (2023). Their study showed that east Uttar Pradesh experienced negative departure from 2001 to 2020 with an exception in some years. Hourly RF analysis of some megacities of Uttar Pradesh was conducted by Kant (2018).

Singla et al. (2014) conducted an analysis of the probability of RF for one to five consecutive days in the Gandak river basin during the years 1969 to 2005. Their study demonstrated that Normal distribution was the optimal fit for one consecutive day, GEV distribution for two consecutive days, and GPAR distribution for three, four, and five consecutive days. The probability analysis of Allahabad district (Uttar Pradesh) spanning 34 years from 1980 to 2013

has been conducted by Asim et al. (2015). Their research showed that GD was the best modal for the best model for the prediction of annual maximum RF and the second-best fit was Log Normal. In a recent study, of annual maximum RF in the Junagadh region of Gujarat state for 38 years (1984 -2021) done by Gundalia et al. (2024), Their study also showed that the GD was found to the best modal for predicting one to five consecutive days for monthly and annual maximum RF.

In Uttar Pradesh, the hourly RF in northern and eastern part from the period 1969-2014 has been done by Kant et al. (2018), In another study, The probability of annual maximum RF using frequency (1991-2000) for Roorkee district of Uttarakhand has been done by Kaur et al. (2021)**,** and showed that the GD provided the most accurate fit for forecasting yearly maximum RF.

The harmonic analysis of precipitation climatology in South Arabia of twenty stations of 30 years has been done by Tarawneh et al. (2016), the annual RF is used to detect RF regimes and climate features using the technique of harmonic analysis in Saudi Arabia. Their research shows that the southwestern area is an entirely distinct climate zone. Conditions in the East and Northwest regions are predominantly influenced by Mediterranean weather patterns, whereas the Western region experiences variable conditions due to the Red Sea Trough (RST) during October and November.

In a different study, Fetene Z et al. (2018) conducted harmonic analysis in the Lake Tana Basin, Ethiopia over the period from 1985 to 2015 (31 years). In their work, examined the properties of seasonal and yearly RF patterns from four weather stations, showing that the amplitude of the first harmonic was 173.42, 177.93, 127.77, and 188.78 mm for Debre Tabor, Bahir Dar, Gander, and Dangila, respectively.

RESEARCH GAP:

A major research gap in RF analysis lies in accurately filling missing data gaps in historical RF records, particularly in regions with sparse weather stations, where interpolation techniques

using neighboring stations can be unreliable due to complex topography and microclimates, leading to potential biases in RF trend analysis and climate modeling.

- Effectively recording the frequency and severity of extreme RF events (such as heavy showers) in incomplete datasets can be difficult, possibly leading to an underassessment of their influence on flood risk evaluation.
- Data gaps can occur sporadically throughout a time series, making it difficult to apply consistent gap-filling methods and potentially introducing biases in trend analysis.
- Quantifying the uncertainty associated with gap-filling techniques to provide more reliable estimates and inform decision-making.

RESEARCH OBJECTIVES:

The objective of RF analysis in research is to understand patterns, trends, and variations in RF over time.

- **Agriculture**: RF data can help with agriculture, especially in areas where rivers, lakes, or aquifers are not easily accessible
- **Water resources management**: Seasonal and annual RF patterns can be important for water resource management.
- **Engineering design**: RF information can assist in the design of hydraulic structures, bridges, culverts, canals, stormwater sewers, and drainage systems for roads
- **Climate science**: Analyzing RF data can help understand climate change patterns and predict future weather conditions.
- **Urban planning**: RF data can help with urban planning

RESEARCH METHODOLOGY:

Statistical techniques in the analysis of RF are crucial for forecasting severe weather events, creating infrastructure (such as dams and drainage systems), and developing strategies for climate adaptation. Integrating conventional statistical methods with contemporary machine learning and GIS-oriented techniques improves precision and dependability in predictions and

risk evaluations. The RF information for different districts was obtained from the India Meteorological Department in Pune and New Delhi. The RF data was examined according to monthly, seasonal, and yearly patterns. An extensive trend evaluation of Delhi and Meerut city is performed utilizing the non-parametric M-K test along with Sen's Slope Estimator. This study also seeks to determine the best probability distribution for predicting annual maximum RF over one day, two successive days, and three successive days, while evaluating the goodness of fit through Chi-Square, Percentage Absolute Deviation (PAD), and Integral Square Error.

M-K test, RF variability, Regression, Correlation, Return Period, various types of distributions like Gumbel, Ven Te Chow, Log Normal etc. Some details are given below.

Return Period:

Return period is calculated by Weibull formula, the Weibull formula for the return period is given below $P = \frac{m}{m+1}$ where m is the number of years as record.

And the return period or recurrence interval is $T = \frac{1}{P}$

Where P represents the probability of an event being equal to or greater than. In this approach, the data was organized in descending order of size and designated the order number 1 to m correspondingly.

Mann- Kendall test:

The M-K test is a statistical non-parametric method utilized for identifying trends in time series data (Mann, 1945; Kendall, 1975; Gilbert, 1987). It is commonly utilized in environmental sciences, hydrology, and climate research to examine long-term patterns in temperature, precipitation, river discharge, and various other environmental factors.

The M-K test whether to accept the alternative hypothesis H_1 and to reject the null hypothesis H_O.

H_O: No monotonic trend

H_1: Monotonic trend is present

a). Arrange the data in the sequence they were gathered over time $x_1, x_2, \ldots \ldots . . x_n$, representing the measurements taken at times 1, 2, 3,…..n correspondingly

b). Determine; $x_2 - x_1,\ \ x_3 - x_2,\ \ \ldots\ldots\ldots x_n - x_{n-1}$

c). The indication function $sgn(x_j - x_k)$ takes the value 1, 0 or -1 according to the sign of $x_j - x_k$ is positive, zero or negative.

d). Calculate $S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$

e). The test statistic Z is computed by the formula-

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & if\ S > 0 \\ 0 & if\ \ S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & if\ S < 0 \end{cases}$$

A positive Z value signifies an upward trend, while a negative Z value signifies a downward trend at the significance level α. When $|Z| > Z_{1-\alpha/2}$. The null hypothesis is dismissed, and a notable trend is present at either the 1% or 5% significance level. If $|Z| < Z_{1-\alpha/2}$. The alternative hypothesis is dismissed and no trend is exist.

Merits of the M-K test

- Handles incomplete data.
- Appropriate for data that is not normally distributed.
- Not affected by seasonal variations in the dataset.

Limitation

- Does not show the extent of the trend (only its existence).
- Aware of serial correlation in data (can result in exaggerated trends).
- Extensive datasets can be demanding on computational resources

Overview of different probability distribution functions:

Distribution	Probability density function (PDF)	Range	Formula for the parameters based on the basic moment
Gumbel	$f(x) = \frac{1}{\alpha} \exp\left[-\frac{x-\mu}{\alpha} - exp\left(-\frac{x-\mu}{\alpha}\right)\right]$	$-\infty < x < \infty$	$\mu = \bar{x} - 0.5772\alpha,$ $\alpha = \frac{S_x\sqrt{6}}{\pi}$

Gamma	$f(x) = \frac{\lambda^{\beta} x^{\beta-1} e^{-\lambda x}}{\Gamma(\beta)}$	$x \geq 0$	$\lambda = \frac{\bar{s}}{s_x^2}$
Log -Pearson type-III	$f(x) = \frac{1}{ay\sqrt{(b)}}\left(\frac{y-c}{a}\right) e^{-\frac{1}{2}\left(\frac{y-c}{a}\right)}$ where $y = logx$	$0 < x < \infty$	$\mu = \bar{x}, \sigma = S_x$
Log- Normal	$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2}$ where $y = logx$	$x > 0$	$\mu_y = \bar{y}, \sigma_y = S_y$
Exponential	$f(x) = \lambda e^{-\lambda x}$	$x \geq 0$	$\lambda = \frac{1}{\bar{x}}$

Ven Te Chow method:

The Expected RF of the variate X is calculated by the equation

$X_T = A + BZ$ Where A and B are constant and determined by the equations:

$$A = \left\lfloor \sum \frac{X_i}{N} \right\rfloor - \left\lfloor B \sum \frac{Z_i}{N} \right\rfloor \quad \text{and} \quad B = \frac{\sum Z_i X_i - \sum Z_i \sum \frac{Z_i}{N}}{\sum Z_i^2 - \frac{\sum Z_i^2}{N}}$$

To test the Goodness to fit:

a). Chi- Square test:

Chi- square test can be used to check the goodness to fit between expected RF and observed RF. The formula of chi- square test is given below-

$$\chi^2 = \sum \frac{(R_O - R_E)^2}{R_E},$$

Where R_O = Observed RF and R_E = Expected RF

b). Percentage Absolute Deviation:

Percentage absolute deviation can be used to test the goodness to fit. It can be calculated by the formula is given below-

$$PAD = \frac{|R_O - R_E|}{R_O} \times 100,$$

c). Integral Square Error:

The Integral Square Error can be employed to assess the quality of fit between anticipated RF. The calculated RF using the formula is provided below

$$ISE = \frac{[\sum_{i=1}^{m}(R_{Ei}-R_{Oi})^2]^{\frac{1}{2}}}{\sum_{i=1}^{m} R_{Oi}},$$

Where R_{Oi} andR_{Ei} are observed RF and expected RF respectively.

Expected Outcomes of the Research:

- More accurate RF predictions can help with irrigation scheduling and water resource management.
- Statistical analysis of RF data can help determine the input values for engineering structures like bridges, canals, and storm water sewers.
- RF analysis can help understand how climate change affects water resources, ecosystems, floods, and droughts
- RF analysis can help identify trends in RF, such as increases or decreases in mean RF over time.
- RF analysis can help identify RF variability, which can be influenced by factors like deforestation, global warming, and urbanization.
- RF analysis can help identify RF patterns, such as normal, deficit, excess and seasonal RF.
- RF analysis can help identify the most effective RF prediction models, such as Logistic Regression and Neural Network models.
- Extreme weather events can impact education outcomes through school closures, compromised access, and destruction of school structures.
- Extreme weather events can disrupt food distribution and increase the risk of food poisoning

The field of extreme weather event research has grown rapidly since the first attribution study in 2004. Scientists use climate models to simulate extreme events and compare them to model runs of the same event in a world without human-caused warming.

Proposed Time Frame:

Year	Plan of Research Work
First	Course work, Literature Survey & Python programming
Second	Visit the India Meteorological Department in New Delhi for data collection and organize the data based on tasks.
Third	Analyzing & Publishing Research Work
Fourth	Thesis Writing and Submission

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Supervisor: Deepak Kumar Department: Applied Sciences, SET

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Application of Statistical Methods in Rainfall Analysis and Extreme Weather Events

SHORT SYNOPSIS

by

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Registration number: 21/Ph.D/112

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ABSTRACT

Rainfall (RF) analysis can have many benefits, including Climate predictions, urban planning, water resource management, transportation safety, disaster risk reduction, agriculture production, etc. Due to population growth, urbanization, and development, the demand for water is increasing in this area day by day. Statistical techniques are vital for examining RF trends and severe weather events. They assist in comprehending historical patterns, forecasting future occurrences, and evaluating risks linked to climate fluctuations. Thus, analyzing the probability of RF is essential to tackle various water management problems and to prevent crops from damage caused by excessive RF. A trend analysis is

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